(51) International Patent Classification 6 :		(11) International Publication Number: **WO 99/18701**
H04L 27/00, H04M 11/06, H04L 1/12	**A1**	(43) International Publication Date: 15 April 1999 (15.04.99)

(54) Title: SPLITTERLESS DIGITAL SUBSCRIBER LINE COMMUNICATION SYSTEM
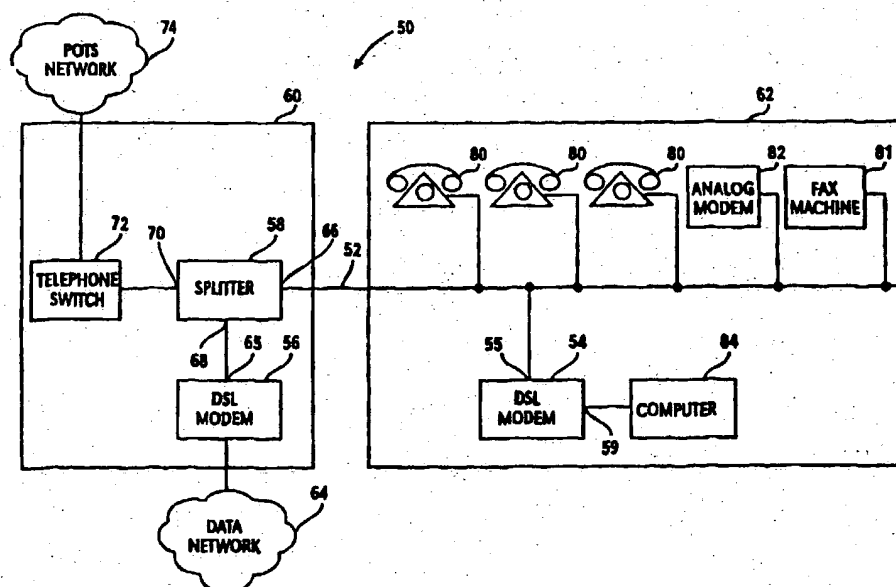
(57) Abstract

A digital subscriber line communication system does not require the use of a plain old telephone service (POTS) splitter in the resident's home. Digital signal processing techniques are utilized to adapt to varying subscriber line conditions due to POTS telephone equipment. The digital signal processing techniques eliminate the need for a splitter by reducing susceptibility to distortion due to varying subscriber line characteristics. The digital subscriber line modem utilizes quadrature amplitude modulated (QAM) signals and frequency division multiplexing. The digital subscriber line modem includes a control circuit which includes a rapid retrain circuit. The rapid retrain circuit can retrain the digital subscriber line modem in less than 0.5 seconds.

SPLITTERLESS DIGITAL SUBSCRIBER
LINE COMMUNICATION SYSTEM

FIELD OF THE INVENTION
The present invention relates generally to communication systems. More particularly, the present invention relates to a digital subscriber line modem.

BACKGROUND OF THE INVENTION
5 Explosive growth of the internet and the worldwide web is driving a need for increased communication data rates. In the corporate world, the need for high-speed access or data rates is met by 10 dedicated high-speed links (perhaps T1/E1 frame relays or OC1 ATM systems) from the company to an internet access provider. Users in the company utilize a local area network (LAN) to gain access to an internet access router which is attached to the high-speed link. Unfortunately, 15 home users of the internet do not often have a high-speed link and must rely on standard analog or plain old telephone service (POTS) line.

The need for high-speed access to the home is ever increasing due to the availability of information, 20 data, programs, entertainment, and other computer applications on the worldwide web and the internet. For example, designers of web technology are constantly developing new ways to provide sensory experiences, including audio and video, to users of the web (web 25 surfers). Higher-speed modems will be required so the home user can fully interact with incoming web and communication technologies.

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Although designers of modems are continuously attempting to increase data rates, analog or POTS line modems are presently only able to reach data rates of up to 56 kilobits per second (Kbps). These conventional analog modems transmit and receive information on POTS subscriber lines through the public switched telephone network. The internet access provider is also coupled to the switched telephone network and transmits and receives information through it to the subscriber line.

Some home users have utilized ISDN equipment and subscriptions to obtain up to 128 Kbps access or data rates by the use of 2 B channels. ISDN equipment and subscriptions can be expensive and require a dedicated subscriber line. Heretofore, neither ISDN modems nor analog modems are capable of providing 256 Kbps or higher access between the home and the internet. Over one megabit per second (Mbps) data rates with analog modems or ISDN equipment do not seem feasible at this time.

A variety of communication technologies are competing to provide high-speed access to the home. For example, asymmetric digital subscriber lines (ADSL), cable modems, satellite broadcast, wireless LANs, and direct fiber connections to the home have all been suggested. Of these technologies, the asymmetric digital subscriber line can utilize the POTS subscriber line (the wire currently being utilized for POTS) between the home user (the residence) and the telephone company (the central office).

ADSL networks and protocols were developed in the early 1990's to allow telephone companies to provide video-on-demand service over the same wires which were being used to provide POTS. ADSL technologies include discrete multitone (DMT), carrierless amplitude and phase modulation (CAP), high-speed ADSL (HADSL), and other technologies. Although the video-on-demand market has been less than originally expected, telephone companies have recognized the potential application of ADSL

technology for internet access and have begun limited offerings.

ADSL technology allows telephone companies to offer high-speed internet access and also allows telephone companies to remove internet traffic from the telephone switch network. Telephone companies cannot significantly profit from internet traffic in the telephone switch network due to regulatory considerations. In contrast, the telephone company can charge a separate access fee for ADSL services. The separate fee is not as restricted by regulatory considerations.

With reference to FIGURE 1, a conventional asymmetric ADSL (ADSL) system 10 includes a copper twisted pair analog subscriber line 12, an ADSL modem 14, an ADSL modem 16, a band splitter 18, and a band splitter 20. Line 12 is a POTS local loop or wire connecting a central office 32 of the telephone company and a user's residence 22.

ADSL modem 14 is located in user's residence 22 and provides data to and from subscriber line 12. The data can be provided from line 12 through modem 14 to various equipment (not shown) coupled to modem 14. Equipment, such as, computers, network devices, servers, or other devices, can be attached to modem 14. Modem 14 communicates with a data network (not shown) coupled to modem 16 across line 12. ADSL modem 16 receives and transmits signals to and from line 12 to the data network. The data network can be coupled to other networks (not shown), including the internet.

At least one analog telephone 26, located in residence 22, can be coupled to subscriber line 12 through splitter 20 for communications across line 12 with telephone switch network 28. Telephone 26 and telephone switch network 28 (e.g., public-switched telephone (PST) network) are conventional systems well-known in the art. Alternatively, other analog

equipment, such as, facsimile machines, POTS modems, answering machines, and other telephonic equipment, can be coupled to line 12 through splitter 20.

System 10 requires that band splitter 18 and band splitter 20 be utilized to separate higher frequency ADSL signals and lower frequency POTS signals. For example, when the user makes a call from residence 22 on telephone 26, lower frequency signals (under 4 kilohertz (kHz)) are provided through band splitter 20 to subscriber line 12 and through band splitter 18 to telephone switch network 28. Band splitter 18 prevents the lower frequency POTS signals from reaching ADSL modem 16. Similarly, band splitter 20 prevents any of the POTS signals from reaching modem 14.

ADSL modem 16 and ADSL modem 14 communicate higher frequency ADSL signals across subscriber line 12. The higher frequency ADSL signals are prevented from reaching telephone 26 and telephone switch network 28 by band splitters 20 and 18, respectively. Splitters 18 and 20 can be passive analog filters or other devices which separate lower frequency POTS signals (below 4 kHz) from higher frequency ADSL signals (above 50 kHz).

The separation of the POTS signals and ADSL signals by splitters 18 and 20 is necessary to preserve POTS voice and data traffic and ADSL data traffic. More particularly, splitters 18 and 20 can eliminate various effects associated with POTS equipment which may affect the transmission of ADSL signals on subscriber line 12. For example, the impedance of subscriber line 12 can vary greatly as at least one telephone 26 is placed on-hook or off-hook. Additionally, the changes in impedance of subscriber line 12 can change the ADSL channel characteristics associated with subscriber line 12. These changes in characteristics can be particularly destructive at the higher frequencies associated with ADSL signals (e.g., from 30 kHz to 1 megahertz (MHz) or more).

Additionally, splitters 18 and 20 isolate
subscriber line wiring within residence 22. The
impedance of such wiring is difficult to predict.
Further still, the POTS equipment, such as, telephone 26,
5   provides a source of noise and nonlinear distortion.
Noise can be caused by POTS voice traffic (e.g.,
shouting, loud laughter, etc.) and by POTS protocol, such
as, the ringing signal. The nonlinear distortion is due
to the nonlinear devices included in conventional
10   telephones. For example, transistor and diode circuits
in telephone 26 can add nonlinear distortion and cause
hard clipping of ADSL signals. Telephone 26 can further
generate harmonics which can reach the frequency ranges
associated with the ADSL signals. The nonlinear
15   components can also demodulate ADSL signals to cause a
hiss in the audio range which affects the POTS.

Conventional ADSL technology has several
significant drawbacks. First, the costs associated with
ADSL services can be quite large. Telephone companies
20   incur costs related to central office equipment (ADSL
modems and ADSL network equipment) and installation costs
associated with the ADSL modems and network equipment.
Residential users incur subscriber equipment costs (ADSL
modems) and installation costs.

25   Installation costs are particularly expensive
for the residential user because trained service
personnel must travel to residence 22 to install band
splitter 20 (FIGURE 1). Although band splitter 18 must
be installed at the central office, this cost is somewhat
30   less because service personnel can install band splitter
18 within central office 32. Also, at office 32,
splitter 18 can be included in ADSL modem 16. However,
in residence 22, splitter 20 must be provided at the end
of subscriber line 12.

35   Additionally, ADSL equipment for the residence,
such as, modem 14, is expensive because the most complex
component of modem 14 (e.g., the receiver) is located at

residence 22 since high-speed transmissions are generally
received within residence 22, and lower-speed
transmissions are received by central office 32. In most
internet applications, larger amounts of data are
requested by the residential user rather than by the
internet source. Receivers are typically much more
complex than transmitters. These high-speed receivers
often receive data at rates of over 6 Mbps.

          ADSL equipment can be subject to cross-talk
noise from other subscriber lines situated adjacent to
subscriber line 12. For example, subscriber lines are
often provided in a closely contained bundle. The close
containment can cause cross-talk from other subscriber
lines to be placed on subscriber line 12. Modem 14 must
compensate for cross-talk noise.

          Thus, there is a need for a digital subscriber
line (DSL) communication system which does not require
the use of a splitter in the residence. Further, there
is a need for a communication system which allows a DSL
modem to be connected directly to the subscriber line
similar to the use of a conventional analog modem. Even
further, there is a need for a less expensive DSL modem
which does not utilize a considerably expensive high-
speed receiver which operates at data rates over 2 Mbps.
Further still, there is a need for a DSL modem which is
not susceptible to errors due to POTS activity on the
subscriber line.

                    SUMMARY OF THE INVENTION

          The present invention relates generally to a
digital subscriber line modem adapted to be coupled
directly to a subscriber line. The modem is capable of
simultaneous access to the subscriber line with other
telephone equipment operating in a frequency band below
4,000 kilohertz. The modem includes a data terminal for
coupling to the subscriber line and a control circuit
coupled to the data terminal. The control circuit

receives and transmits signals to and from the data
terminal. The control circuit utilizes digital signal
processing techniques to adapt to varying subscriber line
characteristics. The digital signal processing

5   techniques allow the data terminal to be coupled directly
to the subscriber line without the use of a splitter.

        The present invention further relates to a
digital subscriber line modem adapted to be coupled
directly to a subscriber line. The modem is capable of

10   simultaneous access to the subscriber line with other
telephone equipment operating in a frequency band below 4
kilohertz. The modem includes a data terminal or
subscriber line access adapted to be coupled to the
subscriber line and a control means for receiving and

15   transmitting signals to and from the data terminal. The
control means includes an equalizer means for filtering
the signals to accommodate characteristics of the
subscriber line, an error processing means for providing
a rapid retrain signal in response to an error condition,

20   and a rapid retrain means for rapidly converging the
equalizer means in response to the rapid retrain signal.
The control means allows the data terminal to be coupled
directly to the subscriber line without the use of a
splitter.

25   The present invention even further relates to a
communication system for use with a subscriber line. The
communication system includes a user digital subscriber
line modem located at a user site, a splitter located
remotely from the user site, and an office digital

30   subscriber line modem. The user digital subscriber line
modem is coupled directly to the subscriber line and
receives downstream signals from the subscriber line and
transmits upstream signals to the subscriber line. The
user digital subscriber line modem utilizes digital

35   signal processing techniques to adapt to varying
subscriber line characteristics. The digital signal
processing techniques allow the data terminal to be

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coupled directly to the subscriber line without the use
of a splitter between the subscriber line and the user
digital subscriber line modem. The splitter has a signal
terminal, a lower-frequency path terminal, and a higher-
frequency path terminal. The signal terminal is coupled
to the subscriber line. The lower-frequency path
terminal is coupled to a switched telephone network. The
office digital subscriber line modem is coupled to the
higher-frequency path terminal. The office digital
subscriber line modem transmits the downstream signals to
the subscriber line through the splitter and receives the
upstream signals from the subscriber line through the
splitter.

The present invention still further relates to
a customer asymmetric digital subscriber line modem for
use in a communication system, including a subscriber
line coupled between an office site and a user site. The
communication system includes a splitter located remotely
from the user site. The splitter has a signal terminal,
a lower-frequency path terminal, and a higher-frequency
path terminal. The signal terminal is coupled to the
subscriber line. The lower-frequency path terminal is
coupled to a telephone switch network. The communication
system also includes an office asymmetric digital
subscriber line modem coupled to the higher-frequency
path terminal. The office digital subscriber line modem
transmits downstream signals to the subscriber line
through the splitter and receives upstream signals from
the subscriber line through the splitter. The customer
asymmetric digital subscriber line modem includes a data
terminal for coupling directly to the subscriber line and
a control circuit. The control circuit is coupled to the
data terminal. The control circuit receives the
downstream signals in a first frequency range and
transmits the upstream signals in a second frequency
range. The control circuit utilizes digital signal
processing techniques to adapt to varying subscriber line

characteristics. The digital signal processing techniques allow the data terminal to be coupled directly to the subscriber line without the use of a splitter at the user site.

According to an exemplary aspect of the present invention, the communication system allows POTS signals and ADSL signals to be simultaneously transmitted on a subscriber line without the use of a splitter located in the user's residence. Digital signal processing techniques are utilized to adapt to the varying subscriber line characteristics due to the activity of POTS equipment coupled to the subscriber line. The digital signal processing techniques eliminate the need for the splitter by changing data transmission characteristics in accordance with the varying line characteristics.

According to another exemplary aspect of the present invention, the DSL modem utilizes quadrature amplitude modulated (QAM) signals provided over the subscriber line. The DSL modem transmits DSL signals in a first frequency range and receives DSL signals in a second frequency range in accordance with frequency division multiplexing techniques. The QAM signals are communicated in various constellation sizes from 4 to 256 points.

In accordance with yet another exemplary aspect of the present invention, the DSL modem includes a rapid retrain circuit. The rapid retrain circuit rapidly retrains the modem-to-subscriber line characteristics in as little time as less than 500 milliseconds. Additionally, an automatic gain control (AGC) circuit, which can be adjusted very rapidly, can also be provided. The rapid retrain circuit preferably eliminates steps related to initially converging the equalizer to reduce retrain times. For example, the rapid retrain circuit may only adjust the AGC and converge the equalizer, starting at predicted coefficients. Echo canceling is

advantageously not needed because the modem transmits and
receives in different frequency rates in accordance with
frequency division multiplexing techniques.

In accordance with still another exemplary
aspect of the present invention, the ADSL modem adjusts
transmission rates in accordance with errors received on
the digital subscriber line. The ADSL operates in
accordance with a state diagram, wherein the data rate is
decreased in response to error signals and increased when
a mean square error is below a threshold. The ADSL modem
consistently monitors error signals to transmit and to
receive at an optimal data rate.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be further described with
reference to the accompanying drawings, wherein like
numerals denote like elements, and:

Fig. 1 is a schematic block diagram of a prior
art ADSL communication system;

Fig. 2 is a schematic block diagram of a
communication system in accordance with an exemplary
embodiment of the present invention, the communication
system includes a DSL modem in accordance with another
exemplary embodiment of the present invention;

Fig. 3 is a more detailed schematic block
diagram of the DSL modem illustrated in FIGURE 2, the DSL
modem includes a control circuit in accordance with yet
another exemplary embodiment of the present invention;

Fig. 4 is a more detailed schematic block
diagram of the control circuit illustrated in FIGURE 3;
and

Fig. 5 is a state diagram showing an example of the operation of the DSL modem illustrated in Fig. 3.

DETAILED DESCRIPTION OF PREFERRED
EXEMPLARY EMBODIMENTS

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With reference to FIGURE 2, a DSL communication system 50 includes a copper twisted pair subscriber line 52, a customer or residential DSL modem 54, a central

10 office DSL modem 56, and a band splitter 58. Subscriber line 52 is a local loop, such as, a twisted pair of American wire gauge (AWG) 24 or 26 copper wires, which connects a central office 60 and a residence 62. Residence 62 can also be an office, building, or other

15 facility. Similarly, central office 60 can be any facility associated with a provider of telephone services.

DSL modem 56 is coupled to a data network 64. Splitter 58 has a signal input 66 coupled to subscriber

20 line 52, a higher-frequency output 68 coupled to DSL modem 56, and a lower-frequency output 70 coupled to a telephone switch 72. Telephone switch 72 is coupled to a POTS network 74. DSL modem 56, splitter 58, and telephone switch 72 are preferably located in central

25 office 60. Alternatively, splitter 58 could be included as part of DSL modem 56 (e.g., DSL modem 56 is provided as an in-line device between subscriber line 52 and switch 72).

In residence 62, one or more telephones 80,

30 analog facsimile machine 81, and analog modem 82 can be coupled directly to subscriber line 52 as is well known in the art. Telephones 80 can be any conventional communication devices, including answering machines, which can be coupled to subscriber line 52 for providing

35 various POTS functions.

DSL modem 54 is coupled directly to subscriber lin 52 at a data terminal, input/output or subscriber line access 55. DSL modem 54 is also coupled to a

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computer 84. Alternatively, DSL modem 54 could be
coupled to other devices (not shown), such as, a network,
server, or other communication or computing device.

Unlike conventional ADSL or DSL communication
systems, such as, system 10 described with reference to
FIGURE 1, DSL modem 54 does not utilize a splitter
between modem 54 and subscriber line 52 and between
telephones 80 and subscriber line 52. DSL modem 54
advantageously utilizes digital signal processing
techniques to adapt to varying subscriber line
characteristics due to analog equipment, such as,
telephones 80, machine 81, and modem 82, thereby
eliminating the need for a splitter in residence 62. DSL
modem 54 can operate concurrently with any of telephones
80, machine 81, and analog modem 82.

DSL modem 54 preferably includes subscriber
line access 55 which is part of a standard connector,
such as, an RJ11 walljack, and is coupled to subscriber
line 52 similarly to conventional telephones 80 and
analog modems 82. Access 55 is preferably a two-wire
terminal.

Modem 54 can be provided as an internal device
in computer 84, such as, on a PCI card, or as an external
device. Preferably, modem 54 is an internal device so
that high speed communications between modem 54 and
computer 84 are not slowed by serial ports associated
with computer 84. As an external device, modem 54 could
be coupled through a printer port or a universal serial
bus (USB) to computer 84. In FIGURE 3, modem 54 is
coupled to computer 84 via a data terminal 59.

Modem 54 is preferably implemented with a
digital signal processing chip set. Other suitable
processors can be utilized to run software modules to
implement the operations described in the present
application. The software modules implement most tasks
associated with modem 54. The tasks include digital
filtering, line characterization, modulation,

demodulation, gain control, equalization, initialization error correction, test functions, and other modem requirements.

In operation, modem 54 adjusts operating characteristics, such as, equalization parameters, gain, and data rates, according to variables associated with line 52. Modem 54 is capable of receiving data at least at a one megabit per second (Mbps) data rate when line 52 is approximately 12 kilofeet and when all of telephones 80 are on-hook. Preferably, the reception (downstream) data rate is no worse than 256 Kbps data rate in the presence of POTS-related impairments associated with telephones 80. Modem 54 is capable of transmitting data at least at a 100 Kbps data rate when line 52 has a length of 12 kilofeet and when all telephones 80 are on-hook. The transmission (upstream) data rate is preferably no worse than 64 Kbps in the presence of POTS-related impairments. By utilizing lower data rates than maximum ADSL data rates, such as, 6 Mbps, modem 54 can be manufactured less expensively and is more able to withstand POTS-related impairments.

DSL modem 56 is similar to DSL modem 54. However, modem 56 preferably is a lower-power modem to minimize the power consumed by central office 60. Additionally, modem 56 can have a sleep mode so that when modem 56 is not being accessed, significant power is not consumed by modem 56. Modem 56 can have a lower-cost receiver unit (not shown) because upstream data rates are lower than downstream data rates, as discussed above. In the sleep mode, processors and other electronic devices in modem 56 are placed in a low-power or no-power mode by slowing or stopping clock signals within modem 56. If modem 54 is utilized within a laptop computer, lower-power techniques are desirable for modem 54 as well.

Modem 54 advantageously utilizes digital signal processing techniques to characterize and to classify interference sources going both to the POTS portion of

the spectrum from the DSL portion of the spectrum and
from the POTS portion of the spectrum to the DSL portion
of the spectrum. Modem 54 compensates for these
interference sources with digital signal processing
techniques. For example, when telephone 80 is brought
off-hook, an impedance change occurs on line 52. Modem
54 can adjust data rates, gain characteristics, and
filter parameters to compensate for the impedance change.
Thus, modem 54 can utilize digital signal processing
techniques to compensate for interference from POTS
equipment, such as, telephone 80. Preferably, the
digital signal processing techniques can rapidly adjust
to interference sources so communication latency are not
noticeable to the user.

            In operation, DSL modems 54 and 56 communicate
signals as quadrature amplitude modulated (QAM) signals.
DSL modems 54 and 56 communicate data at various
constellation sizes, ranging from 4 to 256 UC points.
The data is transmitted in Reed-Solomon frames, where the
R-S code rate is 0.941176471 (K/N) and N = 68 and K = 64.
Alternatively, other values for N and K can be utilized
to optimize data and frame rates.

            DSL modem 54 transmits upstream signals in a
lower-frequency range and receives downstream signals in
a higher-frequency range, in accordance with frequency
division multiplexing techniques. For example, modem 54
preferably transmits upstream signals at a carrier
frequency between a lower band edge of 46 kHz and an
upper band edge of 114 kHz. Modem 54 transmits upstream
signals at a line rate (e.g., bandwidth or data rate) of
136 Kbps for a constellation size of 4 points and at a
data rate of 340 Kbps for a constellation size of 32
points. Modem 56 receives the upstream signals at the
same rates.

            DSL modem 56 transmits downstream signals at a
carrier frequency between a lower band edge of 265.5 kHz
and an upper band edge of 605.5 kHz. DSL modem 56

transmits downstream signals at data rate of 680 Kbps for a constellation size of 4 points and at a data rate of 1.7 Mbps for a constellation rate of 32 points. Modem 54 receives the downstream signals at the same rates. A variety of carrier frequencies can be utilized, such as, 342 kHz, 367.5 kHz, or 418.5 kHz for transmitting downstream information. The use of frequency division multiplexing eliminates the need for an echo canceler (not shown) and eliminates nonlinear effects of echo canceling.

Modems 54 and 56 can utilize a variety of protocols to transmit and receive upstream and downstream signals. Modems 54 and 56 could additionally utilize a auxiliary channel within a control frequency band for transmitting control information between modems 54 and 56. Modems 54 and 56 can also utilize various error protocol, such as, Read-Solomon coding, multidimensional trellis coding, or other protocols, to gain higher immunity to noise and other phone line impairments. Trellis coding is a method of forward error correction where each signal element is assigned a coded binary value representing the element's phase and amplitude. The coding allows the receiving modem to determine, based on the value of the receiving signal, whether or not a given signal element is received in error.

With reference to FIGURE 3, modem 54 includes a high-pass filter 57 coupled between access 55 which is coupled to subscriber line 52 and a control circuit 92. High-pass filter 57 preferably has a threshold frequency above 4 kHz and beneath the lowest band carrier edge for the DSL signals (e.g., 46 kHz) to prevent POTS signal from entering modem 54. Control circuit 92 includes a rapid retrain module or circuit 94, an error processor 96, a line characterization module or circuit 104, and an equalizer 98. Additionally, an automatic gain control circuit (AGC) 102 is disposed between high-pass filter 57 and equalizer 98.

Circuit 102 can be an analog circuit.
Alternatively, circuit 102 can be a digital circuit
located in control circuit 92 or a hybrid analog and
digital circuit. Filter 57 can be a passive filter with
a threshold frequency of 10 kHz.

Equalizer 98 is a digital filter through which
signals are transmitted and received to and from line 52.
Equalizer 98 can be on a receive side of control circuit
92, a transmit side of control circuit 92, or both.
Equalizer 98 is an adaptive compensation circuit for
counteracting distortions on line 52.

Equalizer 98 is preferably a decision feedback
equalizer defined by tap coefficients. Equalizer 98 is
implemented by a digital signal processor (not shown)
running a software program. In the receive mode,
equalizer 98 provides filtered signals to error processor
96 as well as other portions of control circuit 92. The
filtered signals are processed by circuit 92 and provided
at data terminal 59. In the transmit mode, other filters
or equalizers can filter or pre-emphasize signals
provided by modem 54 to line 52.

Equalizer 98 must be converged (e.g., tuned) so
the constellation associated with QAM signals are
appropriately situated for decoding. Alternatively,
equalizer 98 can be any device, digital or analog, for
reducing frequency or phase distortion, or both, on
subscriber line 52 by the introduction of filtering to
compensate for the difference in attenuation or time
delay, or both, at various frequencies in the
transmission and reception spectrums.

Rapid retrain circuit 94 provides control
signals (e.g., tap coefficients) to equalizer 98 to
converge equalizer 98, thereby compensating for
distortion on line 52. Rapid retrain circuit 94 causes
equalizer 98 to converge in response to a raise rate
rapid retrain signal provided by error processor 96 on a
line 97. Rapid retrain circuit 94 also causes equalizer

98 to converge in response to a lower rate rapid retrain
signal provided by error processor on a line 95. Rapid
retrain circuit 94 can utilize tap coefficients developed
by line characterization circuit 104. As discussed in
more detail below, circuit 104 can store a number of
coefficients for known error conditions in a flash memory
or other storage device. Alternately, the coefficients
can be interactively determined, as discussed below.

Error processor 96 monitors signals from
equalizer 98 to determine if significant errors in the
communication of data on line 52 are occurring. If
significant errors are occurring, a lower rate rapid
retrain signal is provided on line 95 so rapid retrain
circuit 94 retrains modem 54. If few errors are
occurring, and data is communicated at a lower data rate,
a raise rate retrain signal is provided on line 97 so
circuit 94 retrains modem 54 so data is communicated at a
higher rate.

As part of the retrain operation, modem 54
performs a variety of tasks to ensure accurate data
communication. A retrain operation for modem 54 can
include the following tasks: reacquiring timing from a
remote modem, such as, modem 56, converging equalizer 98,
and adjusting the data rate. Additionally, the retrain
operation can also include characterizing line 52 and
adjusting the automatic gain control circuit 102.
Depending on modem 54 and line 52 parameters, circuit 94
can perform different levels of retrain operations.

In a slow retrain or initialization operation,
a retrain operation from initiation variables (e.g.,
scratch) of modem 54 can include reacquiring timing,
characterizing line 52, adjusting circuit 102 from
initialization variables, converging equalizer 98 from
initialization variables, and determining a data rate.
Characterizing line 52 can involve performing line
characterization routines by circuit 104, as discussed
below. Since adjustments to circuit 102 and converging

equalizer 98 is an interactive process, these procedures
can be time-consuming. The slow retrain can take as long
6.5 seconds. Nonetheless, time is saved, even in the
slow retrain operation when compared to conventional
5   modems, because modem 54 advantageously does not utilize
an echo canceler (not shown). The echo canceler
typically must be reset during a retrain operation.

        To save time, a rapid-retrain operation can
eliminate one or more of the above steps or perform the
10   above steps from predicted variables (variables which are
initially closer to the desired value than initialization
variables). In a rapid retrain operation, the line
characterization step is eliminated, and circuit 102 and
98 are adjusted slightly or converged from a stored
15   coefficient. For example, according to a rapid retrain
operation, the center tap coefficient for equalizer 98
can be determined, and the remaining coefficients can be
adjusted based on the difference between the determined
center tap coefficient and the previous center tap
20   coefficient.

        According to another rapid retrain operation,
prestored tap coefficients are utilized so equalizer 98
does not have to be significantly converged. The tap
coefficients are chosen based upon conditions recognized
25   by circuit 94, such as, telephone 80 (FIGURE 2) being
brought off-hook. The adjustment of the gain circuit 102
can be restricted to a range to save time.

        System and application parameters associated
with modem 54 and line 52 can define the amount of time
30   required for a rapid retrain of modem 54. For example, a
rapid retrain may occur in a particular amount of real
time, such as, less than 0.5 seconds. A rapid retrain
within 0.5 seconds assures that the transmission of data
is not affected for perceivable delays as modem 54 is
35   retrained. A 0.5 second retrain operation is a vast
improvement over the conventional 6.5 seconds for
initialization retrain operations. Alternatively, the

rapid retrain operation may occur in a much shorter time
period, particularly if error processor 96 and rapid
retrain circuit 94 are able to determine what changes on
subscriber line 52 have caused errors. Circuit 94 can
5   react to those changes and access a database or other
data indicative of coefficients for equalizer 98, gain
parameters for circuit 102, data rates, or other criteria
for appropriate communication of data on line 52. For
example, such a database could be stored on computer 84
10   coupled to modem 54 (FIGURE 2). Further still, a very
rapid retrain operation could occur where equalizer 98
does not have to be converged, and only the gain of
circuit 102 needs to be adjusted. Thus, rapid retrain
circuit 94 is capable of retraining modem 54 in a rapid
15   manner in response to error processor 96 discovering that
there are errors in the communication of data on
subscriber line 52.

                When rapid retrain circuit 94 performs a
retrain operation, data rates associated with modem 54
20   are adjusted to maximize the data rate, while maintaining
the integrity of the communications. For instance, if
error processor 96 determines that a particular number of
errors are occurring, rapid retrain circuit 94 may adjust
the data rate down by reducing the size of the
25   constellation or reducing the symbol rate. Error
processor 96 can determine errors which require an
adjustment of equalizer 98, such as, tangential error,
radial error, or other errors. Error processor 96 can
also react to trellis-coding errors, Reed-Solomon errors,
30   mean squared error levels, or other errors.
Alternatively, if error processor 96 determines that the
mean squared error level is below a threshold, rapid
retrain circuit 94 can retrain modem 54 and adjust the
data rate upward by increasing the size of the
35   constellation or increasing the symbol rate. The
threshold used to compare the mean squared error, as well

as other errors, is variable according to user parameters
and the data rate.

Line characterization circuit 104 can perform a
variety of operations to characterize line 52 for the
development of tap coefficients for equalizer 98 and of
other parameters for modem 54. Line characterization
tests can be performed when modem 54 is at
initialization, in an idle mode, or in a non-idle mode.
According to one line characterization test, tones or
test patterns are transmitted across line 52 in
accordance with a test protocol. Modems 54 and 56
cooperate to determine characteristics of line 52 based
upon received tones or test patterns. In a non-idle
mode, the test pattern can be sent and analyzed during
the time the user is awaiting communications from the
Internet. Further, a separate control channel can be
utilized to send control information necessary to
characterize line 52.

In another embodiment, circuit 104 can enter a
learn mode and analyze line 52 under a variety of
conditions. While in the learn mode, the user can bring
telephone 80 (FIGURE 2) off-hook in response to
instructions generated by software on computer 84. Modem
54 can characterize line 52 during those particular
conditions. Coefficients for equalizer 98 can be
generated for those conditions and stored for a rapid
retrain operation. Further still, circuit 104 can
perform line-probing operations similar to the V.34
standard.

In yet another embodiment, an echo canceler
(not shown) can be utilized on a transmit side of modem
54 to remove the transmitted signals in the transmit
frequency spectrum. Control circuit 92 can analyze the
characteristics in the transmit frequency spectrum of
line 52. This analysis can be performed during non-idle
modes. The portion of equalizer 98 on the transmit sid
can be adjusted according to the analysis to predistort

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or to preemphasize the transmitted signals. Digital
frequency processing techniques can also include various
error signal analysis, correction, and manipulation to
determine when a rapid retrain is necessary as well as
techniques for rapidly converging an equalizer associated
with modem 54.

     With reference to FIGURE 4, error processor 96
includes a Reed-Solomon decoder 120, a mean squared error
calculator 122, and a Trellis decoder 124. Reed-Solomon
decoder 120 analyzes frames of data provided from error
decoder 124 and determines if a frame error occurs and if
errors are occurring in the frame. Reed-Solomon decoder
120 can correct errors as is well known in the art.
Alternatively, calculator 122 can be replaced by other
systems which can provide an indication of signal-to-
noise ratios.

     Reed-Solomon decoder 120, calculator 122, and
Trellis decoder 124 provide a lower rapid retrain signal
when error conditions indicate that the data rate should
be lowered. Rapid retrain circuit 94 performs a rapid
retrain operation and lowers the data rate in response to
the lower rate rapid retrain signal at input 95. In
contrast, when the mean squared error calculator 122
provides a raise rate rapid retrain signal at input 97,
rapid retrain circuit 94 raises the data rate and
performs a rapid retrain. Thus, modem 54 automatically
raises or lowers its data rate to maintain high-speed and
accurate communications in the presence of POTS-related
impairments.

     Although the data rates associated with modems
54 and 56 are somewhat lower than maximum data rates
associated with conventional ADSL systems, these data
rates are still significantly larger than conventional
analog modem capabilities. The lower data rates allow
modems 54 and 56 to use smaller constellation sizes and
frequency division multiplexing, as well as withstand
POTS-related impairments.

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Digital signal processing techniques can
include rapid retrain operations where the modem is
adjusted to changing subscriber line techniques due to
POTS operations. Such adjustments can include adjusting
5   automatic gain control circuit 102, converging equalizer
98, and error processing. Further, digital signal
processing techniques can include line characterization
techniques performed by circuit 104 (FIGURE 3).

        With reference to FIGURE 5, operation of modem
10   54 is described with reference to FIGURES 2-5. FIGURE 5
is a state diagram showing rapid retrain operations for
modem 54. Modem 54 preferably always provides the
highest data rate available on line 52, according to a
rate-adaptive digital subscriber line technique. Modem
15   56 should have the ability to set a maximum downstream
data rate so that the telephone company can limit the
maximum downstream data rate to avoid advantaging
subscribers who live close to office 60. According to
this technique, modems 54 and 56 constantly adjust the
20   data rates to reach maximum data rate potential on
subscriber line 52 (FIGURE 2).

        In FIGURE 5, modem 54 (FIGURE 2) is capable of
a start-up state 100, an idle state 102, a data mode
state 104, a fast retrain reduce rate state 106, and a
25   fast retrain increase rate state 108. When off or idle,
modem 54 transfers from idle state 102 to start-up state
100 when it receives a start-up command.

        In start-up state 100, modem 54 is initialized.
During initialization, timing is acquired from a remote
30   modem, such as, modem 56, automatic gain circuit 102 is
adjusted, equalizer 98 is converged, the carrier phase is
locked, line 52 is characterized, and a data rate is
selected. If start-up is successfully completed, modem
54 advances to data mode state 104, where data is
35   communicated across subscriber line 52.

        As data is communicated at the data rate
selected during start-up state 100, error signals from

error processor 92 are consistently checked. If the
error signals are within an acceptable level, modem 54 is
maintained in data mode state 104. However, if the error
signals are above a particular level, modem 54 enters
5   fast retrain reduce rate state 106. In state 106, modem
54 reduces the data rate, adjusts automatic control
circuit 102, re-acquires timing, and converges equalizer
98. Preferably, equalizer 98 is retrained from stored
coefficient values to reduce the amount of time required
10   for retraining. Alternatively, another mode (not shown)
may be entered where just the automatic gain control 102
(FIGURE 3) is adjusted, and the data rate is not changed
to compensate for errors.

In state 106, if the fast retrain fails,
15   another fast retrain is attempted. If more than two fast
retrain attempts fail, modem 54 returns to start-up state
104. As at initialization, if start-up fails, modem 54
enters idle state 102.

If the fast retrain operation is successfully
20   completed, modem 54 returns to data mode state 104 and
continues to communicate data at a lower data rate. The
data rate can be adjusted incrementally or by other
relationships. For example, if the errors are due to
known POTS activity, particular data rates may be known
25   to operate during that activity, and those data rates may
be chosen.

In state 104, if the mean square error signal
provided by mean square error calculator 122 is below a
threshold, modem 54 enters fast retrain increase rate
30   state 108. Modem 54 is retrained in state 108 similarly
to state 106, except that the data rate is increased. If
the fast-retrain operation is completed successfully,
modem 54 changes from state 108 to state 104 and
continues normal data communication operations at the
35   faster rate. If the fast retrain operation fails in
state 108, modem 54 enters state 106 and performs a fast
retrain reduce rate operation.

It is understood that, while the detailed drawings and specific examples given describe preferred exemplary embodiments of the present invention, they are for the purpose of illustration only. The apparatus and method of the invention is not limited to the precise details and conditions disclosed. For example, although QAM signals and frequency division multiplexing is utilized, other protocols can be implemented. Also, although parameters related to a rapid retrain operation are discussed, the rapid retrain operation may include a variety of steps for ensuring the integrity of the data channel at high data rates. Various changes may be made to the details disclosed without departing from the spirit of the invention which is defined by the following claims.

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CLAIMS

What is claimed is:

1   1. A digital subscriber line modem adapted to be

2   coupled directly to a subscriber line, the modem being

3   capable of simultaneous access to the subscriber line

4   with other telephone equipment operating in a frequency

5   band below four kilohertz, the modem comprising:

6   a data terminal for coupling to the subscriber line;

7   and

8   a control circuit coupled to the data terminal, the

9   control circuit receiving and transmitting signals to and

10   from the data terminal, the control circuit utilizing

11   digital signal processing techniques to adapt to varying

12   subscriber line characteristics, whereby the digital

13   signal processing techniques allow the data terminal to

14   be coupled directly to the subscriber line without the

15   use of a splitter.

1   2. The digital subscriber line modem of claim 1,

2   further comprising:

3   a high pass filter coupled between the data terminal

4   and the control circuit, the high pass filter attenuating

5   lower frequency signals at the data terminal.

1   3. The digital subscriber line modem of claim 2,

2   wherein the high pass filter attenuates the lower

3   frequency signals having a frequency below 46 kHz.

1   4.   The digital subscriber line modem of claim 1,

2   wherein the subscriber line is a twisted pair copper

3   line.

1   5.   The digital subscriber line modem of claim 1,

2   wherein the control circuit transmits and receives the

3   data in a data mode, the control circuit transmitting and

4   receiving the data at data rates, the control circuit

5   adjusting the data rates in response to varying

6   conditions due to the other telephone equipment on the

7   subscriber line.

1   6.   The digital subscriber line modem of claim 5,

2   wherein the varying conditions include changes in the

3   impedance of the subscriber line due to hooking or

4   unhooking the other telephone equipment.

1   7.   The digital subscriber line modem of claim 1,

2   wherein the control circuit further includes a rapid

3   retrain circuit and an error processing circuit, the

4   error processing circuit providing a lower rate retrain

5   signal when the error processing circuit detects a

6   predetermined number of errors associated with the data,

7   wherein the retrain circuit lowers data rates of the

8   modem in response to the lower rate retrain signal.

1   8.   The digital subscriber line modem of claim 1,

2   wherein the control circuit further includes a rapid

1   retrain circuit and an error processing circuit, the

2   error processing circuit providing a raise rate retrain

3   signal when an error signal is below a threshold, wherein

4   the retrain circuit raises the data rates of the modem in

5   response to the raise rate retrain signal.

1   9. The digital subscriber line modem of claim 8,

2   wherein the threshold varies with the data rates, and the

3   error signal is a mean squared error signal.

1   10. The digital subscriber line modem of claim 7,

2   wherein the rapid retrain circuit rapidly retrains the

3   modem in response to the lower rate retrain signal.

1   11. The digital subscriber line modem of claim 10,

2   wherein rapid retraining includes reacquiring timing from

3   a remote unit providing the data on the subscriber line,

4   and converging the equalizer.

1   12. The digital subscriber line modem of claim 11,

2   wherein the rapidly retraining occurs within 500

3   milliseconds.

1   13. The digital subscriber line modem of claim 7,

2   wherein the signals are quadrature amplitude modulated

3   signals and are frequency division multiplexed for

4   transmit signals and receive signals.

1   14.   A digital subscriber line modem adapted to be

2   coupled directly to a subscriber line, the modem being

3   capable of simultaneous access to the subscriber line

4   with other telephone equipment operating in a frequency

5   band below the four thousand kilohertz band, the modem

6   comprising:

7   a data terminal adapted to be coupled to the

8   subscriber line; and

9   a control means for receiving and transmitting

10   signals to and from the data terminal, the control means

11   including an equalizer means for filtering the signals to

12   accommodate characteristics of the subscriber line, an

13   error-processing means for providing a rapid retrain

14   signal in response to an error condition, and a rapid

15   retrain means for rapidly converging the equalizer means

16   in response to the rapid retrain signal, whereby the

17   control means allows the data terminal to be coupled

18   directly to the subscriber line without the use of a

19   splitter.

1   15.   The digital subscriber line modem of claim 14,

2   wherein the equalizer means filters according to

3   coefficients, and the rapid retrain means provides

4   initial coefficients in accordance with a line condition

5   related to the error condition.

1   16.   The digital subscriber line modem of claim 15,

2   wherein the control means further includes a database for

storing the initial coefficients for various line

conditions, the rapid retrain means selecting the initial

coefficients for a particular line condition in response

to the error signal.

17.   The digital subscriber modem of claim 14,

wherein the error processing means monitors a noise

level at an output of the equalizer means.

18.   The digital subscriber line modem of claim 14,

wherein the error processing means receives a Reed-

Solomon error signal or a Viterbi error signal.

19.   The digital subscriber line modem of claim 14,

wherein the rapid retrain means lowers a data rate of the

signals without characterizing the subscriber line.

20.   A communication system for use with a

subscriber line, the communication system comprising:

a user digital subscriber line modem, located at a

user site, the user digital subscriber line mode being

coupled directly to the subscriber line and receiving

downstream signals from the subscriber line and

transmitting upstream signals to the subscriber line and

utilizing digital signal processing techniques to adapt

to varying subscriber line characteristics, whereby the

digital-processing techniques allow the customer digital

subscriber line modem to be coupled directly to the

1   subscriber line without the use of a splitter between the

2   subscriber line and the user digital subscriber modem;

3   a splitter, located remote from the user site, the

4   splitter having a signal terminal, a lower frequency path

5   terminal, and a higher-frequency path terminal, the

6   signal terminal being coupled to the subscriber line, the

7   lower frequency path terminal being coupled to a switched

8   telephone network; and

9   an office digital subscriber line modem coupled to

10   the higher frequency path terminal, the office digital

11   subscriber line transmitting the downstream signals to

12   the subscriber line through the splitter and receiving

13   the upstream signals from the subscriber line through the

14   splitter.

1   21. The communication system of claim 20, wherein

2   the digital signal processing techniques include rapidly

3   retraining the user digital subscriber line modem in

4   response to varying characteristics of the subscriber

5   line.

1   22. A customer asymmetric digital subscriber line

2   modem for use in a communication system including a

3   subscriber line coupled between an office site and a user

4   site, the communication system including a splitter

5   located remote from the user site, the splitter having a

6   signal terminal, a lower frequency path terminal, and a

7   higher frequency path terminal, the signal terminal being

1 coupled to the subscriber line, the lower frequency path

2 terminal being coupled to a telephone switch network, the

3 communication system including an office asymmetric

4 digital subscriber line modem coupled to the higher

5 frequency path terminal, the office digital subscriber

6 line modem transmitting downstream signals to the

7 subscriber line through the splitter and receiving

8 upstream signals from the subscriber line through the

9 splitter, the customer asymmetric modem comprising:

10   a data terminal for coupling directly to the

11 subscriber line; and

12   a control circuit coupled to the data terminal, the

13 control circuit receiving the downstream signals in a

14 first frequency range and transmitting the upstream

15 signals in a second frequency range, the control circuit

16 utilizing digital signal processing techniques to adapt

17 to varying subscriber line characteristics, whereby the

18 digital processing techniques allow the data terminal to

19 be coupled directly to the subscriber line without the

20 use of splitter at the user site.

1   23.   The modem of claim 22, wherein the upstream

2 signals and downstream signals are quadrature amplitude

3 modulated signals.

1   24.   The modem of claim 22, further comprising:

2   a high pass filter coupled between the data terminal

3   and the control circuit, the high pass filter attenuating

4   lower frequency signals at the data terminal.

1   25.   The modem of claim 21, wherein the control

2   circuit adjusts data rates of the upstream and downstream

3   signals in response to varying conditions on the

4   subscriber line.

1   26.   The modem of claim 25, wherein the varying

2   conditions include changes in the impedance of the

3   subscriber line due to hooking or unhooking other

4   telephone equipment coupled to the subscriber line.

1   27.   The modem of claim 22, wherein the control

2   circuit further includes a rapid retrain module and an

3   error processing module, the error processing module

4   providing a lower rate retrain signal when the error

5   processing module detects a predetermined number of

6   errors associated with the upstream and downstream

7   signals, wherein the retrain circuit lowers the data

8   rates of the modem and rapidly retrains the modem in

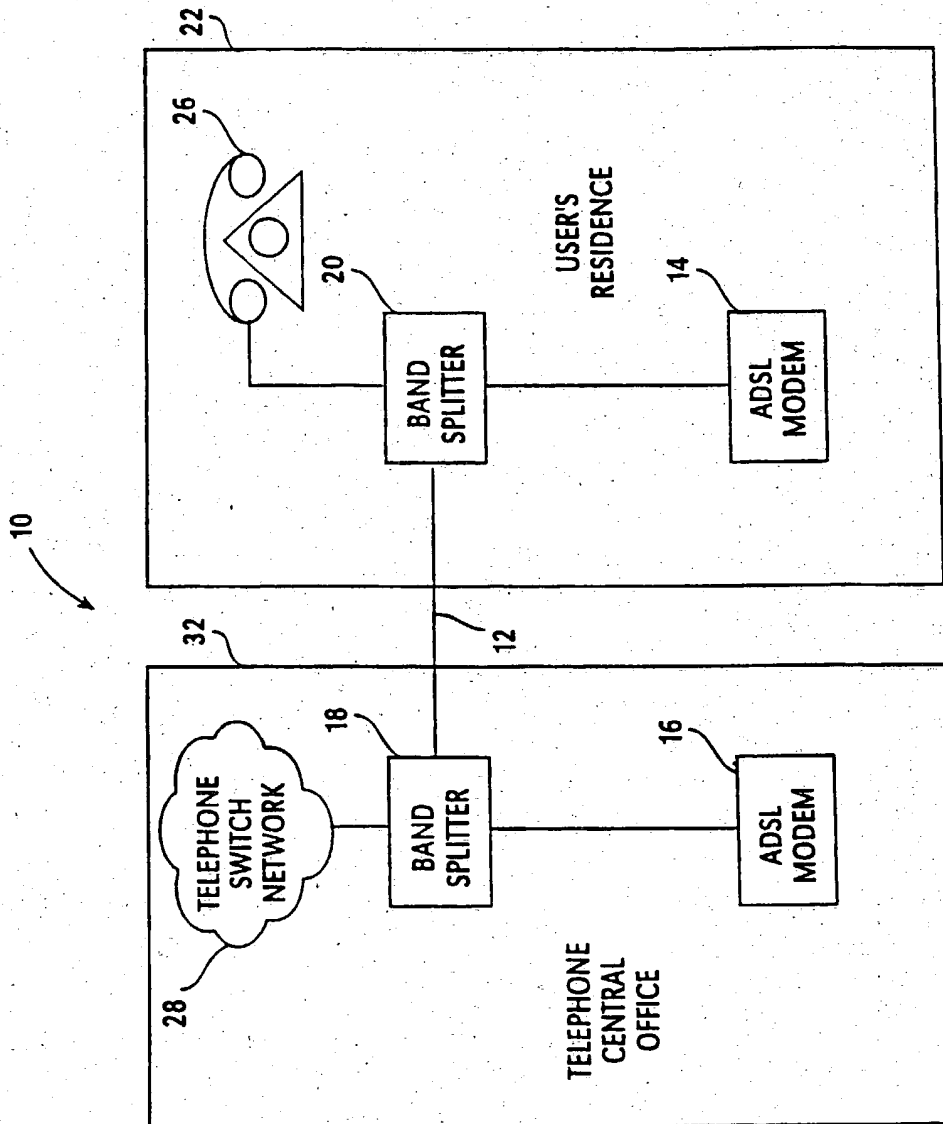9   response to the lower rate retrain signal.

1   28.   The digital subscriber line modem of claim 27,

2   wherein the error processing module provides a raise rate

3   retrain signal when a mean error signal is below a

1 threshold, wherein the retrain circuit raises the data

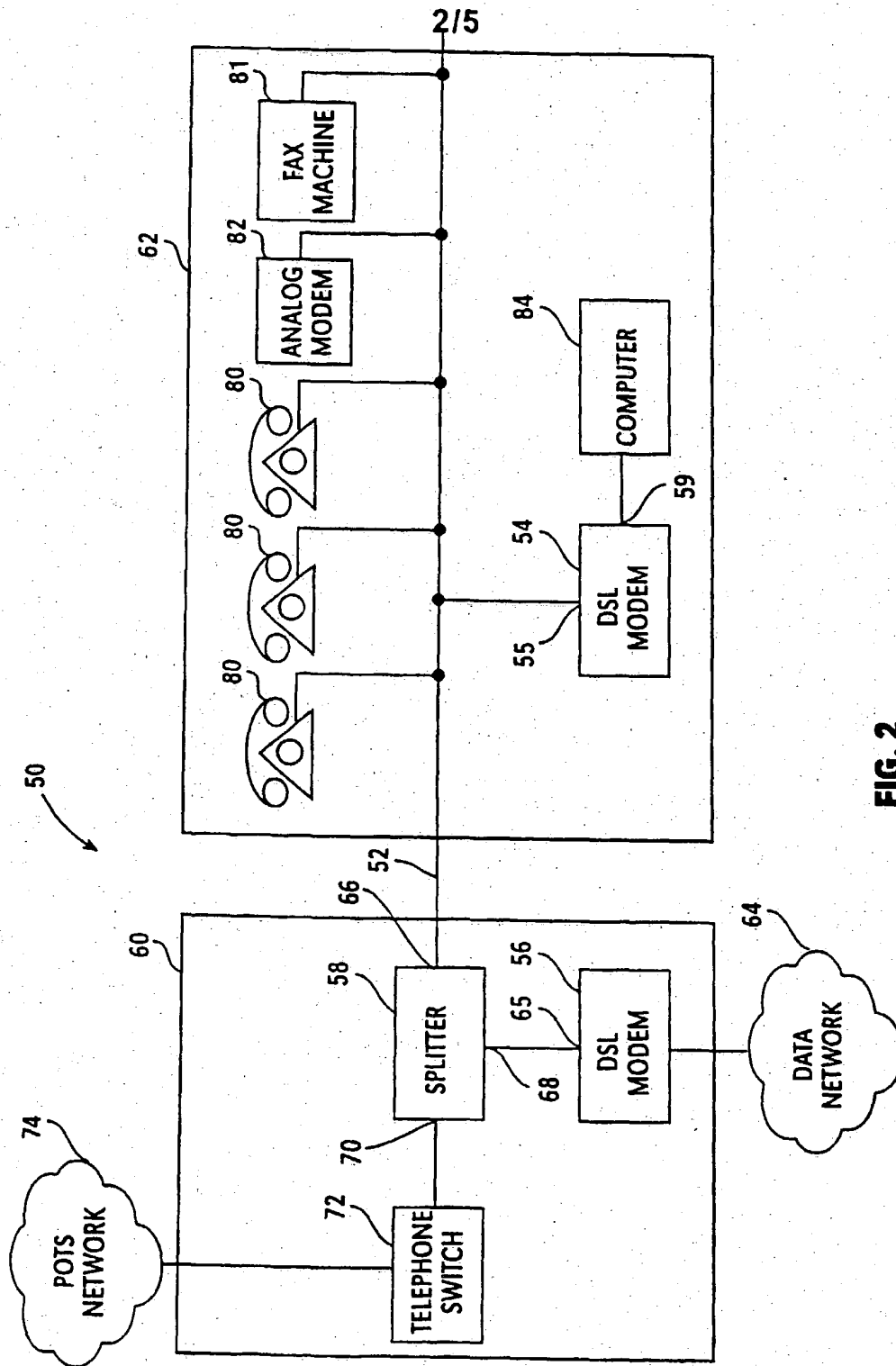2 rates of the modem in response to the raise rate retrain

3 signal.

1 29. A digital subscriber line modem adapted to be

2 coupled directly to a subscriber line, the modem being

3 capable of simultaneous access to the subscriber line

4 with other telephone equipment operating in a frequency

5 band below 4 kHz, the modem comprising:

6 a data terminal for coupling to the subscriber

7 line; and

8 a control circuit coupled to the data terminal

9 to receive and transmit signals therefrom, the control

10 circuit being configured to adapt to characteristics of

11 the subscriber line to receive and transmit digital data

12 from the subscriber line without a splitter coupled

13 between the data terminal and the subscriber line.
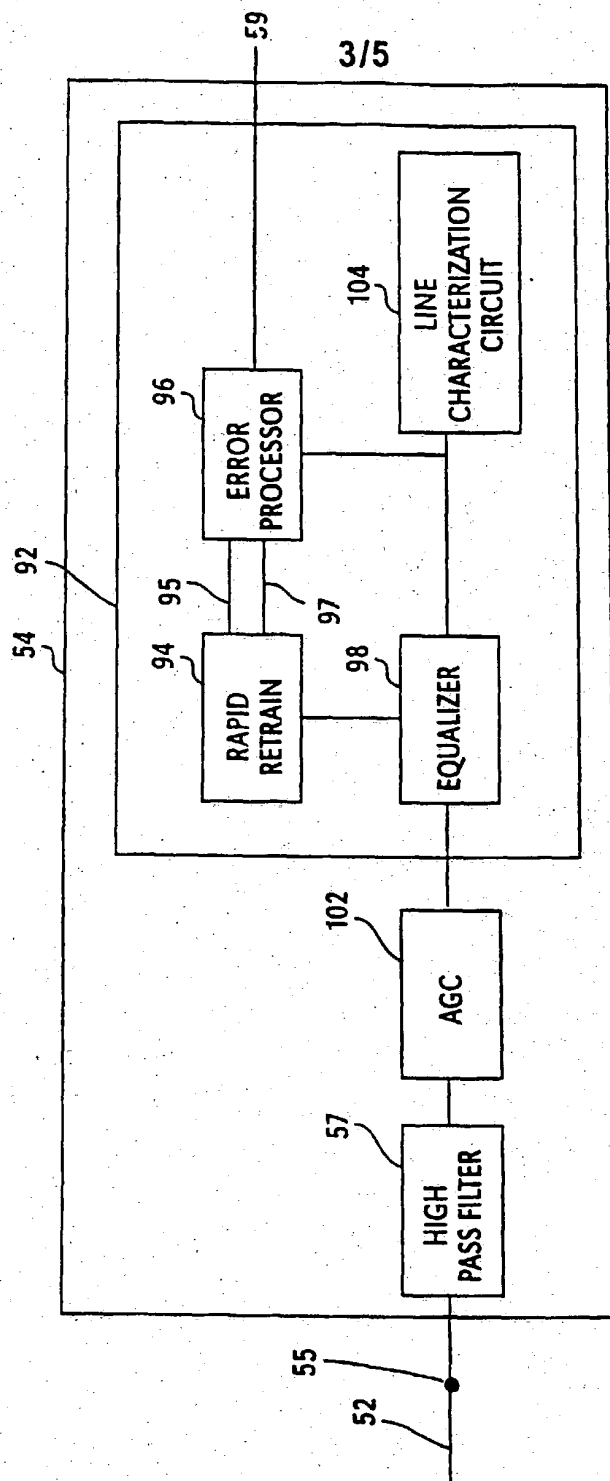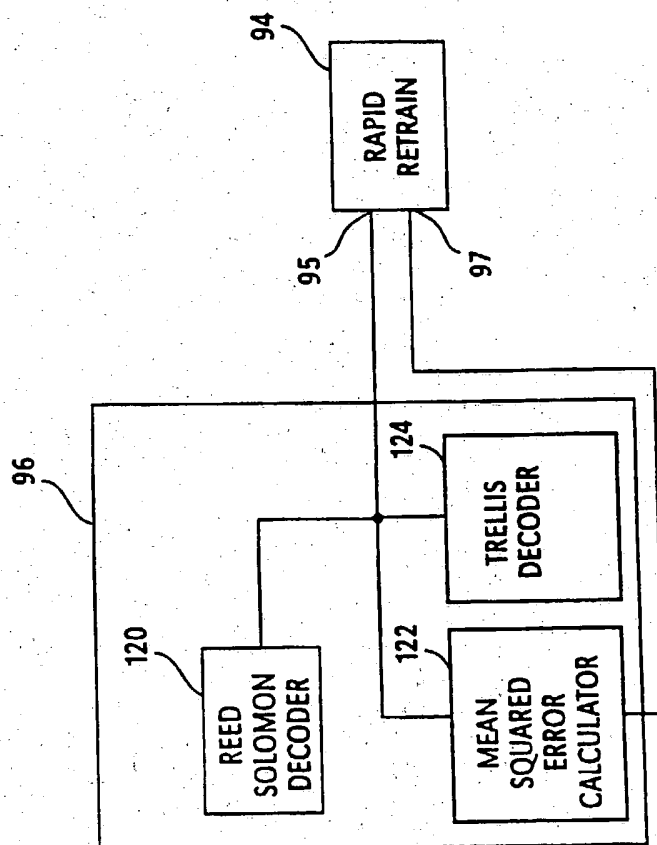
(PRIOR ART)
FIG. 1

FIG. 2
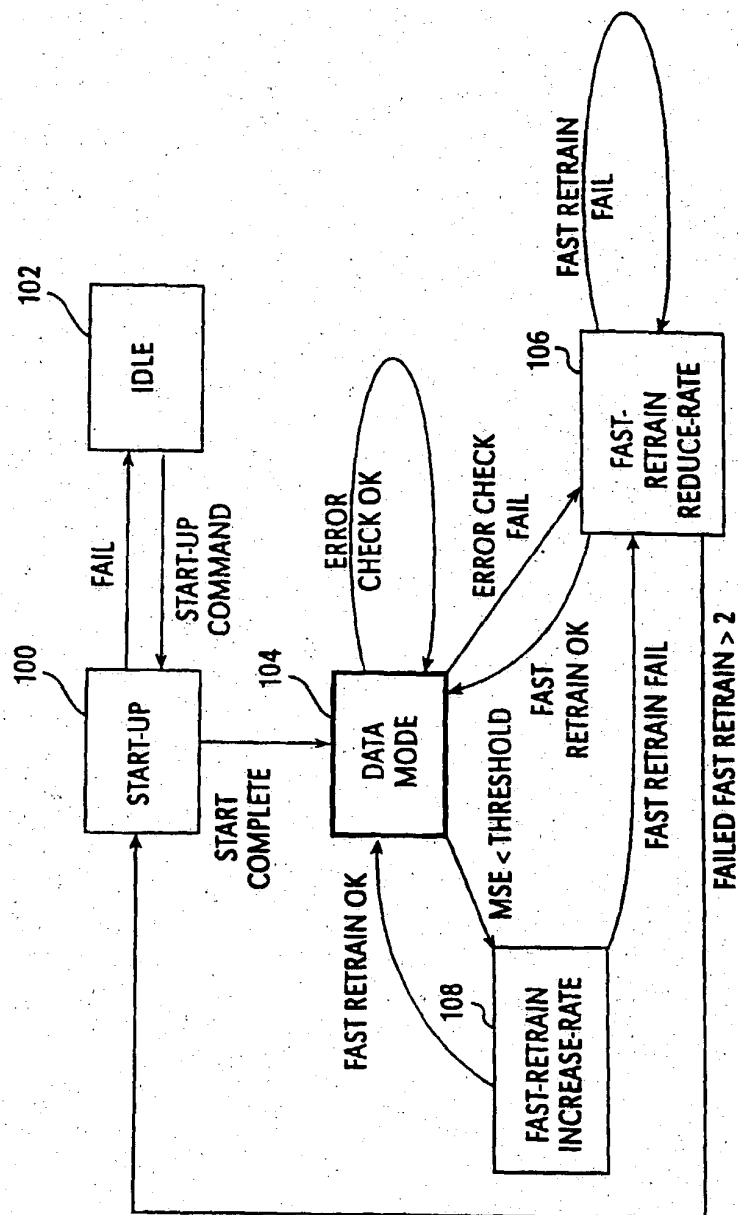
3/5

FIG. 3

FIG. 4

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FIG. 5

IDLE — 102

START-UP — 100

FAIL

START-UP COMMAND

START COMPLETE

DATA MODE — 104

ERROR CHECK OK

ERROR CHECK FAIL

FAST-RETRAIN REDUCE-RATE — 106

FAST RETRAIN FAIL

FAST RETRAIN OK

MSE < THRESHOLD

FAST RETRAIN FAIL

FAILED FAST RETRAIN > 2

FAST-RETRAIN INCREASE-RATE — 108

FAST RETRAIN OK

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H04L27/00   H04M11/06   H04L1/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H04L   H04M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 20396 A (ANALOG DEVICES INC) 5 June 1997 see abstract see page 5, line 5-31 see page 7, line 11-23	1-6, 20-26,29
A	see claims 1-3	7-19,27, 28
P,X	EP 0 820 168 A (TEXAS INSTRUMENTS INC) 21 January 1998 see abstract see page 4, line 40 - page 6, line 20 see page 7, line 1-17 see figure 2A	1-29
E	WO 98 27665 A (PARADYNE CORP) 25 June 1998 see the whole document	1-29

☐ Further documents are listed in the continuation of box C.   ☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 1999	26/01/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl. Fax: (+31-70) 340-3016	Toumpoulidis, T

Form PCT/ISA/210 (second sheet) (July 1992)

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			AU	1079797 A	19-06-1997
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